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TECHNICAL NOTE

D-173

FLIGHT INVESTIGATIONS OF AUTOMATIC STABILIZATION OF AN AIRPLANE HAVING STATIC LONGITUDINAL INSTABILITY

By Walter R. Russell, S. A. Sjoberg,
and William L. Alford

Langley Research Center
Langley Field, Va.

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SUMMARY

A flight research program utilizing a subsonic jet-propelled fighter airplane was conducted to investigate the capabilities of three types of automatic stabilization and control systems in stabilizing airplanes having aerodynamic static longitudinal instability. The systems investigated were a normal-acceleration-command control system, a pitch-rate-command control system, and a pitch-damper system. The center-of-gravity range covered was from about 4 percent of the mean aerodynamic chord forward of the stick-fixed maneuver point of the basic airplane to about 4 percent of the mean aerodynamic chord behind the stick-fixed maneuver point of the basic airplane.

With the center of gravity 4 percent of the mean aerodynamic chord behind the maneuver point and at a Mach number of 0.6 at an altitude of 30,000 feet, the time required for a disturbance in normal acceleration to double in amplitude was about 1 second and the force gradient was about -6 pounds per g. With these stability characteristics the pilots doubted that any type of military mission could be accomplished and felt that landings would be very difficult and dangerous. When flying the unstable airplane with any of the three automatic stabilization and control systems, the flying qualities were definitely superior to those of the basic airplane. The pilots were of the opinion that they could control the unstable airplane through the normal-acceleration control system as easily and accurately as they could control the stable airplane with the manual control system.

INTRODUCTION

The possibility of using an automatic control system to stabilize airplanes which have static longitudinal instability has been recognized for many years but, with the exception of the work reported in reference 1, little has been done in flight to demonstrate this possibility experimentally. The Langley Research Center of the National

Aeronautics and Space Administration has conducted a brief flight research program to investigate the capabilities of three types of automatic longitudinal stabilization systems in stabilizing a fighter airplane whose stability characteristics had been modified to simulate an aerodynamically unstable airplane.

The primary object of the flight program was to determine experimentally the feasibility of using automatic control equipment to stabilize a statically unstable aircraft. A secondary objective was to obtain some information on a pilot's ability to control an airplane which is statically unstable. A subsonic jet-propelled fighter airplane having a straight wing was used for the flight program. L
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One type of airplane for which operation with static longitudinal 3
instability in certain flight regions might be desirable is an airplane 6
which is intended to cruise at supersonic speeds. In the interest of reducing the trim drag at supersonic speeds, the static stability should be low. If the static stability is low at supersonic speeds, the airplane is likely to be unstable at subsonic speeds. It is in the subsonic flight region then that the use of automatic stabilization systems for stability augmentation might be required. One of the main considerations regarding the use of automatic control equipment for this application is, of course, that of reliability. The equipment reliability aspects are not considered in this paper.

SYMBOLS

a_n	normal acceleration, g units
C_N	normal-force coefficient $\frac{Wa_n}{\bar{q}S}$
F_{c_p}	longitudinal controller stick force, lb
F_{s_e}	longitudinal manual stick force, lb
h_p	pressure altitude, ft
M	Mach number
q	pitching velocity, radians/sec
$\dot{q}$	pitching acceleration, radians/sec^2
$\bar{q}$	dynamic pressure, lb/sq ft

V_i indicated airspeed, knots

W airplane weight, lb

S wing area, sq ft

δ_{c_p} longitudinal controller stick position, deg

δ_e elevator position, deg

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δ_{s_e} longitudinal manual stick position, deg

ϕ roll attitude angle, deg

g acceleration due to gravity, ft/sec^2

DESCRIPTION OF AIRPLANE AND AUTOMATIC CONTROL SYSTEMS

Airplane

The airplane used was a subsonic jet-propelled fighter with an unswept wing. A photograph of the airplane is presented in figure 1 and a two-view drawing is presented in figure 2. General dimensions and characteristics of the airplane are listed in table I. The wing-tip fuel tanks were on the airplane for all flights. The basic-airplane control system consisted of hydraulically boosted ailerons with a boost ratio of approximately 37:1, an elevator with a spring tab, bobweight, and down spring, and a conventional manual-type rudder control system. The force-deflection characteristics of the elevator system are presented in figure 3.

Automatic Control Systems

Three longitudinal automatic stabilization and control systems were investigated in the program. Two types of controllers and two lateral-control systems were used in conjunction with the longitudinal stabilization systems. The various combinations used are listed in table II. The first column of table II shows the longitudinal systems tested and the second and third columns show the lateral control system and the controller configuration used with each system. The longitudinal systems are now described in more detail.

The irreversible-power control system was simply the electric servomotor operating as a displacement servo to position the elevator.

Two command automatic longitudinal control systems were used: a normal-acceleration control system and a pitch-rate control system. The normal-acceleration system is described in detail in reference 2 and the pitch-rate system is described in reference 3. Block diagrams of the two command control systems are presented in figures 4(a) and 4(b). Briefly, with these systems the airplane steady-state normal acceleration (in the case of the normal-acceleration control system) or the steady-state pitching velocity (in the case of the pitch-rate control system) is proportional to the fore-and-aft stick deflection. Further, the static sensitivities between normal acceleration or pitching velocity and stick deflection are independent of the airplane flight condition. For control-free (hands-off) flight the normal-acceleration control system attempts to regulate the normal acceleration to the automatic-control-system trim value (normally 1 g) and the pitch-rate system attempts to regulate the pitching velocity to zero. Inner-loop feedback signals proportional to elevator position and rate and, for the normal-acceleration system, pitching velocity are used to increase the stability. For steady-state conditions these signals are washed out.

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A block diagram of the pitch-damper system used is presented in figure 4(c). With this system the elevator displacement was proportional to the sum of the pilot's command signal and the pitch-rate gyro feedback signal. The phasing of the pitch-rate signal was such as to increase the damping in pitch of the airplane. The pitch-rate feedback gain and the stick gain were adjustable in flight. It should be noted that there was no mechanical connection between the pilot's controller and the elevator.

Two lateral-control systems were used in the investigation. One was a roll-rate-command control system (described in ref. 3) and the other an irreversible-power control system (described in ref. 4). For all configurations a yaw damper (described in ref. 5) was used in the rudder channel.

Controllers

A rigid force-type side-located controller was used with the irreversible-power control system and with the pitch-damper system. A photograph of the force-stick controller is shown in figure 5. Strain gages located below the stick grip provided an output signal linearly proportional to the pilot-applied stick force. Hysteresis was negligible. As indicated in table II, two types of force sticks were used. One was the straight steel tube shown in figure 5. The steel tube was 1 inch in diameter and extended 3.8 inches above the armrest. The other was a 1/4-inch steel rod covered with sponge rubber about 1 inch in diameter and extending 3.8 inches above the armrest. The pilots used both force sticks as full-hand grip controllers.

A small side-located displacement-type controller was used by the pilot for introducing electrical signals into the command automatic control systems. The controller is described in detail in reference 4. A photograph of this controller is presented in figure 6 and the force-deflection characteristics are presented in figure 7.

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METHOD

The test airplane was made to have static longitudinal instability by the use of ballast so that the center-of-gravity location was sufficiently far rearward. The flight-operation procedure was to take off with the center-of-gravity location of the airplane near the service rear center-of-gravity limit and then burn fuel from a fuel tank located forward of the center of gravity until the desired center of gravity was attained. The desired center-of-gravity location was maintained during the test runs by using fuel from the wing-tip fuel tanks. The use of fuel from the tip tanks caused very little movement of the center of gravity of the airplane.

The flight tests of the unstable airplane were conducted at Mach numbers between 0.45 and 0.75 at altitudes from about 25,000 feet to 30,000 feet. At these flight conditions maximum lift was attained at load factors considerably below the limit load factor for the airplane. In the event of loss of control by the pilot, the airplane could be made statically stable very quickly by jettisoning ballast from a container located at the rear end of the fuselage. (See fig. 1.) In order to make the airplane stable for landing, fuel was transferred from a tank behind the center of gravity into the forward fuel tank.

INSTRUMENTATION

NASA recording instruments, which measured the following quantities, were installed in the airplane: normal, longitudinal, and transverse accelerations; pitching, rolling, and yawing velocities and accelerations; pitch and bank attitude angles; angle of attack and sideslip angle; airspeed and altitude; elevator, aileron, and rudder positions; longitudinal and lateral stick positions for the conventional control stick; rudder pedal position; longitudinal stick force for the conventional control stick; longitudinal and lateral stick forces for the force-stick controller; longitudinal and lateral stick positions for the side-located displacement stick.

The airspeed head, which was used to measure airspeed and altitude, was mounted on a boom which extended out of the nose of the airplane. (See fig. 1.) No calibration was made of the airspeed installation; therefore, the airspeed and altitude data presented in this paper have not been corrected for position error. It is estimated that the error in the measured static pressure due to the fuselage pressure field is about 2 percent of the impact pressure above true static pressure at low angles of attack. The airplane angle of attack and sideslip angle were measured with vanes which also were mounted on the nose boom.

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RESULTS AND DISCUSSION

Basic Airplane

As indicated in table II, the basic airplane (airplane without any automatic stabilization) was flown with both the standard control stick and a rigid side-located force-type controller. The data presented in this paper for the basic airplane were obtained with the standard control stick unless otherwise indicated.

Flight tests of the basic airplane were conducted at an altitude of about 30,000 feet at a Mach number between 0.45 and 0.75. The center of gravity of the airplane was varied from a normal position of about 27.5 percent of the mean aerodynamic chord to a position of about 36.5 percent of the mean aerodynamic chord. The static stability of the basic airplane was measured in both straight and turning flight. Also, the pilots' opinions of the handling qualities were obtained for cruising flight, in turns, in tracking runs on a target airplane, and in formation flying.

The static longitudinal stability characteristics of the basic airplane in steady 1 g flight at an altitude of about 30,000 feet are shown in figure 8 for center-of-gravity positions of 28, 32, and 35.5 percent of the mean aerodynamic chord. Stability characteristics in turning flight for the same center-of-gravity positions are presented in figure 9. The airplane was trimmed at a Mach number of 0.6 at 30,000 feet. The stick-fixed neutral point is located slightly forward of the 35.5-percent mean-aerodynamic-chord point and the stick-free neutral point is at about 35.5 percent of the mean aerodynamic chord, whereas the stick-fixed maneuver point is at about 32 percent of the mean aerodynamic chord and the stick-free maneuver point is slightly back of 32 percent of the mean aerodynamic chord. The reason for the neutral points being behind the maneuver points is not known but it is believed to be a power effect. With the center of gravity about 4 percent of the mean aerodynamic chord behind the stick-fixed maneuver point, the stick-force gradient was about -6 pounds per g at a Mach number of 0.6 at 30,000 feet. The motions of the basic airplane resulting from small stick pulses are shown in figure 10 for a center-of-gravity position of 36 percent of the mean aerodynamic chord and a Mach number of 0.6 at 30,000 feet. The airplane diverged rapidly, the time for a disturbance in normal acceleration to double in amplitude being about 1 second.

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The pilots were of the opinion that the handling qualities of the basic airplane, when flown with the conventional control stick, were good when the center of gravity was located about 4 percent of the mean aerodynamic chord ahead of the maneuver point. When the airplane was neutrally stable (center of gravity at the maneuver point), the pilots were of the opinion that the handling characteristics were not acceptable for combat operations or any operations involving rapid maneuvers. The characteristics were acceptable but undesirable for operations involving only mild maneuvers such as returning to base and landing even under instrument flight conditions. A summary of pilot's opinions on flying the basic airplane with the conventional control stick with the center of gravity located 4 percent of the mean aerodynamic chord behind the maneuver point is presented. It was necessary for the pilot to give his undivided attention to the task of controlling the airplane when using the standard control system. Since the rate of divergence was very high, it was impossible for the pilot to perform other tasks. It is extremely doubtful whether any type of military mission could be accomplished and landings would be very difficult and dangerous. Instrument flight would not be practicable because of distractions due to navigation, radio operation, and so forth. In rough air the airplane could not be flown for a very long period of time because of pilot fatigue.

When flying with the rigid force-type controller, pilots' opinions were substantially the same as when flying with the standard center-located stick. The steel-tube grip (fig. 5) was superior to the sponge-rubber grip for flying the unstable airplane because it permitted a more rapid response to the pilot's applied forces and thus made it easier to maintain control of the airplane. The steel-tube grip was also superior to the sponge-rubber grip for takeoffs and landings made with the airplane having longitudinal stability. For flight at high dynamic pressures with the stable airplane where the response times of the airplane are short, the sponge-rubber grip was, in the opinion of the pilots, somewhat better than the steel-tube grip. Apparently, the sponge provided some flexibility which reduced the motions of the airplane resulting from inadvertent pilot inputs.

Airplane With Normal-Acceleration Control System

Flight tests of the airplane and the normal-acceleration control system were made at a Mach number range from about 0.5 to 0.75 at altitudes from 25,000 feet to 30,000 feet. The range of center-of-gravity positions was from about 27.5 percent of the mean aerodynamic chord to about 36.5 percent of the mean aerodynamic chord. As indicated in table II a displacement-type side-located controller was used in conjunction with the normal-acceleration control system.

Transient response characteristics of the airplane—normal- L
acceleration-control-system combination are presented in figure 11 for 6
center-of-gravity positions of 28, 32, and 36 percent of the mean aero- 3
dynamic chord. Feedback gains of the system were the same for all 6
three center-of-gravity positions. The static sensitivity of the side controller was slightly lower for the run made with the center of gravity at 28 percent of the mean aerodynamic chord. In the opinion of the pilots, the response characteristics of the airplane were entirely satisfactory. The slight overshoot of the commanded acceleration which occurred with the center of gravity at 36 percent of the mean aerodynamic chord was not objectionable and, in fact, scarcely noticeable. The pilots were of the opinion that they could control the airplane through the normal-acceleration system with the center of gravity 4 percent of the mean aerodynamic chord behind the maneuver point as easily and accurately as they could control the aerodynamically stable airplane with the basic control system. In this regard it should be noted that the basic airplane had good flying qualities.

Flight operations such as cruising, tracking a target airplane, and formation flying were conducted with the normal-acceleration control system, and in the pilots' opinion the characteristics of the unstable-airplane—normal-acceleration-control-system combination were satisfactory for these tasks. Figures 12 and 13 clearly illustrate the differences of the control characteristics of the normal-acceleration control system and the standard control system when the basic airplane is unstable. Figure 12 shows a time history of bank angle, normal acceleration, elevator position and control input during a portion of a left turn made with the normal acceleration system and figure 13 shows a similar record made with the standard control system. In both cases the pilot attempted to hold a constant acceleration. Comparison of the two figures shows that the pilot could maintain a much more constant acceleration with the normal-acceleration system and with much less work.

Airplane with Pitch-Rate Control System

A limited investigation of the characteristics of the pitch-rate control system was made at the same flight conditions as covered with the normal-acceleration system. The same displacement-type side-located controller that was used with the normal-acceleration system was also used with the pitch-rate system. Transient responses for the airplane—pitch-rate-control-system combination for three center-of-gravity positions are presented in figure 14. The system gains were the same for all three runs. The normal acceleration response was comparatively slow for all center-of-gravity positions and, with the center of gravity 4 percent of the mean aerodynamic chord behind the maneuver point, the response was lightly damped. It should be noted that no attempt was made to obtain optimum response characteristics with the pitch-rate system. The pilots were of the opinion that the response characteristics with the pitch-rate system with the center of gravity located 4 percent of the mean aerodynamic chord behind the maneuver point were acceptable but not as satisfactory as with the normal-acceleration system. The response characteristics were, however, much improved from those of the basic airplane.

Airplane with Pitch-Damper System

The pitch-damper system was evaluated in straight and level flight, turns, and pullups at altitudes from 25,000 to 30,000 feet at Mach numbers from about 0.5 to 0.65. The center-of-gravity range covered was from about 33 to 36.5 percent of the mean aerodynamic chord. As indicated in table II the rigid side-located force stick was used with the pitch-damper system.

The response of the airplane—pitch-damper system combination to a near-step input is shown in figure 15. Conditions for this maneuver were: $M = 0.6$; $h_p = 30{,}000$ feet; center of gravity at 36 percent of the mean aerodynamic chord; and pitch-rate feedback gain of 23 volts per radian per second (25° δ_e per radian per second). Although the response was very slow, the pilots were of the opinion that it was acceptable. It should be noted that a more rapid and more desirable type of response would have resulted if a higher pitch-rate gain had been used. Qualitatively, the response is the same as that obtained in a previous theoretical analysis for a different airplane configuration. (See ref. 6.) A comparison of figure 4(b) and figure 4(c) shows that the pitch-damper system and the pitch-rate command system are the same except for the washout circuit on the elevator followup signal of the pitch-rate system. As shown by a comparison of figures 14 and 15, the effect of the washout circuit is to change the dominant mode from a first-order system with a long time constant (pitch-damper system, fig. 15) to a lightly damped second-order system (pitch-rate system, fig. 14).

The stick-fixed static stability data obtained in 1 g flight (see fig. 8) show that the airplane was unstable in forward speed with the center of gravity at 36 percent of the mean aerodynamic chord. A previous theoretical analysis (ref. 6) has indicated that this speed instability associated with the unstable center-of-gravity position might be a problem. The pulse input maneuvers shown in figures 16(a) and 16(b) were made to investigate this speed instability. As the figures show, the airplane-damper system combination was slightly out of trim for these maneuvers and the airplane did not diverge in forward speed following the nosedown pulse. It did diverge following the noseup pulse and the
indicated forward airspeed decreased about 30 knots in 18 seconds. The L
time to double amplitude was estimated to be about 6 seconds. This 6
estimate was made from the last 6 seconds of the record where the effects 3
of the short-period convergent mode were minimum. The rate of divergence 6
of the airspeed was scarcely noticeable to the pilots in normal flying. However, this degree of instability might be objectionable for flight operations where accurate control of airspeed is required.

With the maximum pitch-rate feedback gain and the stick gain which the pilots considered near optimum, the stick force required to hold a steady 2g turn was about 6 pounds for a center-of-gravity position of 36 percent of the mean aerodynamic chord. It is interesting to note that the pilots preferred the same stick gain for all pitch-rate feedback gains between zero and the maximum available. The near-optimum stick gain was equivalent to about 0.15° δ_e per pound, and the maximum pitch-rate feedback gain was equivalent to about 25° δ_e per radian per second. With the center of gravity at 36 percent of the mean aerodynamic chord, about 55 percent of the maximum available pitch-rate gain was required to make the airplane neutrally stable in turning flight. With the maximum available pitch-rate gain, the effective maneuver point was at about 39 percent of the mean aerodynamic chord; that is, the airplane would have been neutrally stable in turning flight with the center of gravity at 39 percent of the mean aerodynamic chord when the maximum available pitch-rate gain was used.

The pilots were of the opinion that the rigid side-located force stick was an effective airplane controller. In general, the lack of stick motion with the force stick was not objectionable for flying the airplane in either the unstable or the stable configuration.

CONCLUSIONS

A flight research program utilizing a subsonic jet-propelled fighter airplane was conducted to investigate the capabilities of three types of automatic control systems in stabilizing an airplane having aerodynamic static longitudinal instability. The automatic control systems investigated included a normal-acceleration-command control system, a pitch-rate-command control system, and a pitch-damper system. The center-of-gravity range covered was from 28 to 36 percent of the mean aerodynamic chord or from about 4 percent of the mean aerodynamic chord forward of the stick-fixed maneuver point of the basic airplane to about 4 percent of the mean aerodynamic chord behind the stick-fixed maneuver point of the basic airplane. The Mach number range covered in the investigation was from 0.45 to 0.75 and the altitude range was from about 25,000 to 30,000 feet. The following conclusions may be made:

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1. With the center of gravity 4 percent of the mean aerodynamic chord in back of the maneuver point and at a Mach number of 0.6 at 30,000 feet, the time required for a disturbance in normal acceleration to double in amplitude was about 1 second and the force gradient was about -6 pounds per g. With these stability characteristics it was necessary for the pilot to give his undivided attention to the task of controlling the airplane with the standard control system (no automatic stabilization). The pilots doubted that any type of military mission could be accomplished and felt that landings would be very difficult and dangerous. When flying with the rigid side-located force stick and the irreversible-power control system, the pilots' opinions were substantially the same as when flying with the standard stick.

2. The handling characteristics associated with the normal-acceleration-command system were satisfactory for all center-of-gravity positions covered in the investigation. The pilots were of the opinion that they could control the unstable airplane through the acceleration-control system as easily and accurately as they could control the stable airplane with the manual control system. In this connection it should be noted that the basic airplane had good flying qualities at stable center-of-gravity locations.

3. The pilots were of the opinion that the response characteristics of the airplane with the pitch-rate system and with the center of gravity at 4 percent of the mean aerodynamic chord behind the maneuver point were acceptable but not as satisfactory as with the normal-acceleration system. At this center-of-gravity position the response of the pitch-rate system was comparatively slow and underdamped. The flying qualities were, however, much improved from those of the basic airplane. It should be noted that no attempt was made to obtain optimum response characteristics with the pitch-rate system.

4. The response characteristics with the pitch-damper system and the rigid side-located force stick were acceptable for all center-of-gravity locations covered in the investigation. The divergence associated with forward speed which occurred when the center of gravity

was located 4 percent of the mean aerodynamic chord behind the maneuver point was not objectionable to the pilot.

5. The pilots were of the opinion that the rigid side-located force stick was an effective airplane controller. In general, the lack of displacement with the force stick was not objectionable when flying the airplane in either the stable or the unstable configuration.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., August 25, 1959.

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TABLE I

GENERAL AIRPLANE DATA

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Wing:	
Span (with tip tanks), ft	37.99
Span (without tip tanks), ft	35.25
Area (without tip tanks), sq ft	250
Airfoil section	NACA 64_1A012
Aspect ratio (without tip tanks)	4.97
Taper ratio	0.46
Incidence, deg	0
Dihedral, deg	4
Twist, deg	0
Sweep of 27-percent-chord line, deg	0
Mean aerodynamic chord (M.A.C.), in.	89.45
Total aileron area, sq ft	18.44
Aileron travel, deg	19 up, 14 down
Horizontal tail:	
Span, ft	17.21
Area (including elevator), sq ft	66.20
Elevator area, sq ft	19.20
Elevator travel, deg	18 up, 15 down
Tail length, 25-percent M.A.C. of wing to elevator hinge line, ft	18.45
Vertical tail:	
Area (not including dorsal fin), sq ft	36.02
Rudder area, sq ft	8.54
Rudder travel, deg	±26
Miscellaneous:	
Length (excluding nose boom), ft	38.13
Weight, takeoff (tip tanks full; 250-lb ballast in tail), lb	15,900
Center-of-gravity position, takeoff, percent M.A.C.	31.5
Engine	J42-P-8

TABLE II

AIRPLANE AND AUTOMATIC STABILIZATION SYSTEM COMBINATIONS INVESTIGATED

Longitudinal control system	Lateral control system	Controller configuration
Basic-airplane system	Basic-airplane power boost system	Standard-airplane control stick
Irreversible-power control system	Irreversible-power control system	Rigid side-located force stick (a) Rigid grip (b) Sponge grip
Normal-acceleration control system	Roll-rate command system or irreversible-power control system	Side-located displacement stick
Pitch-rate control system	Roll-rate command system or irreversible-power control system	Side-located displacement stick
Pitch-damper system (pitch-damper signal not washed out)	Irreversible-power control system	Rigid side-located force stick (a) Rigid grip (b) Sponge grip

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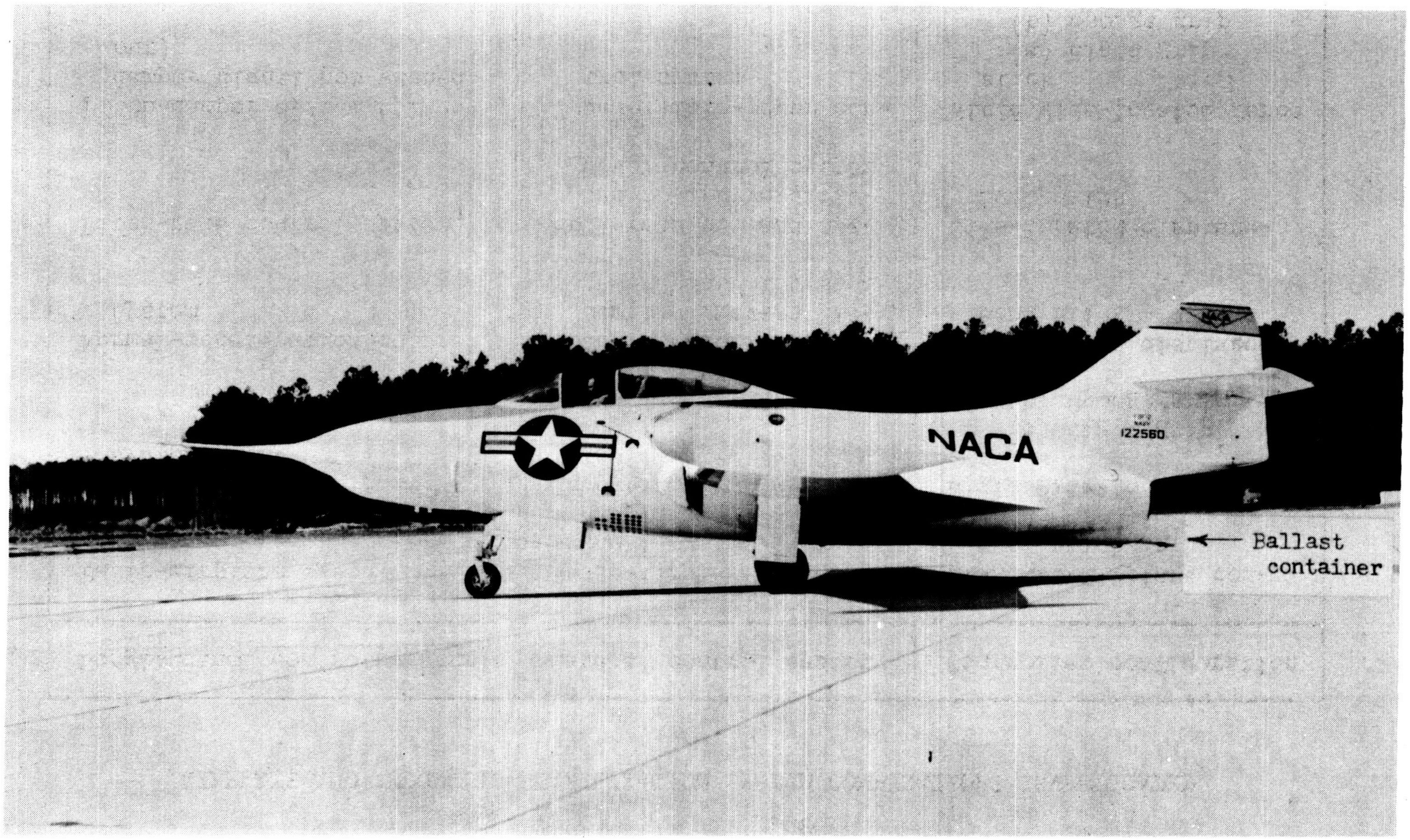

Figure 1.- Side view of airplane. L-58-1840.1

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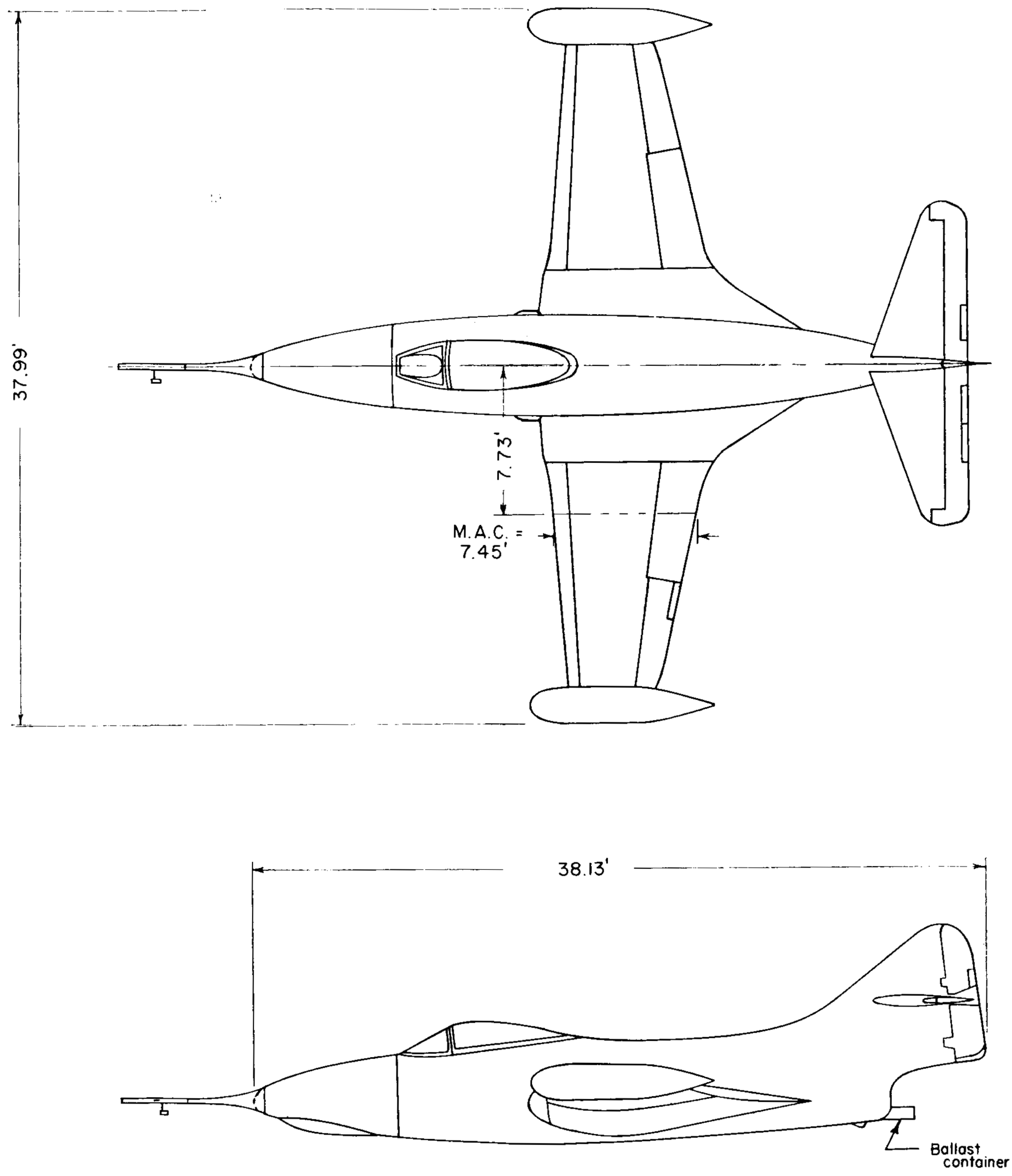


Figure 2.- Two-view drawing of airplane.

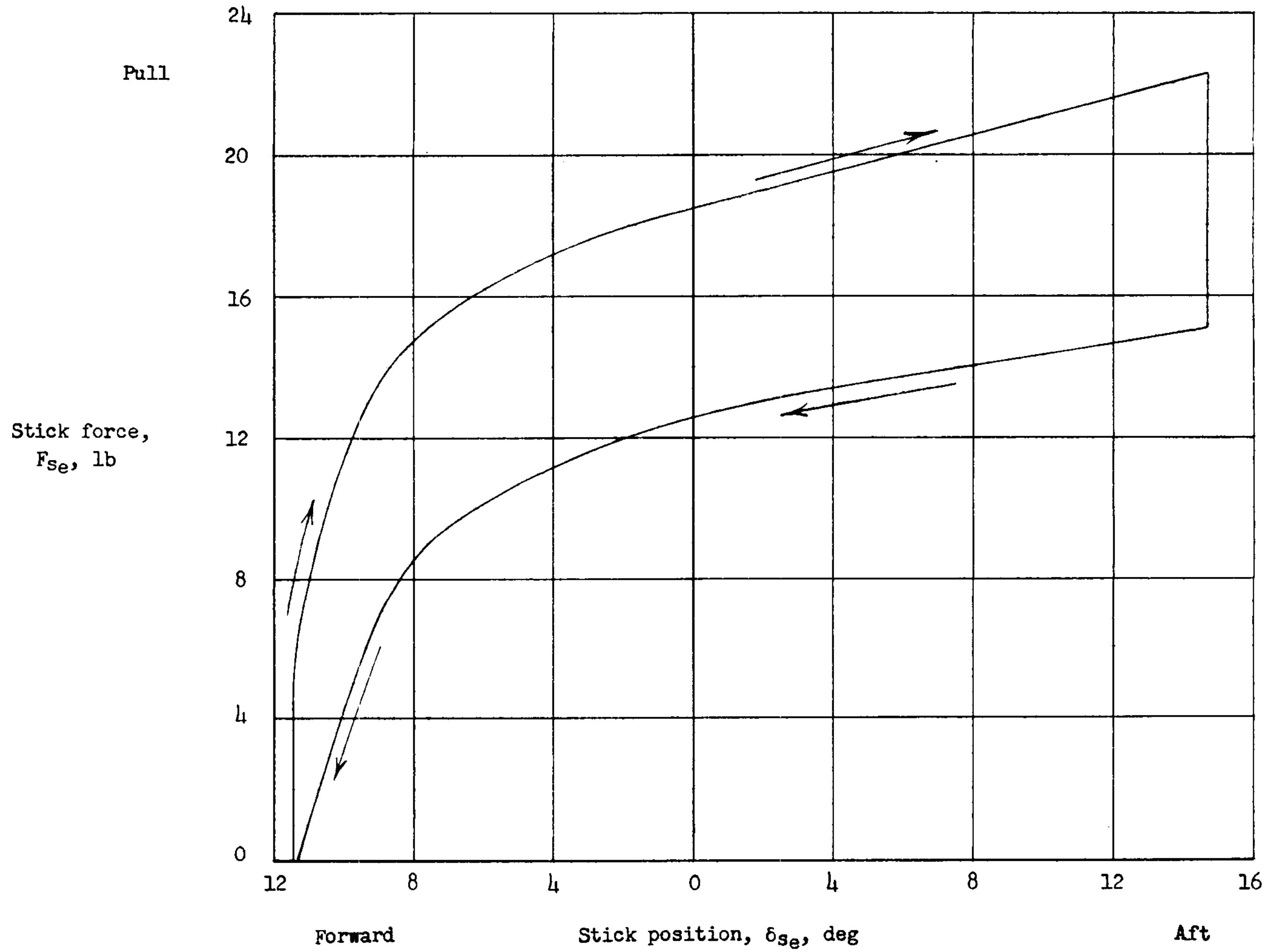
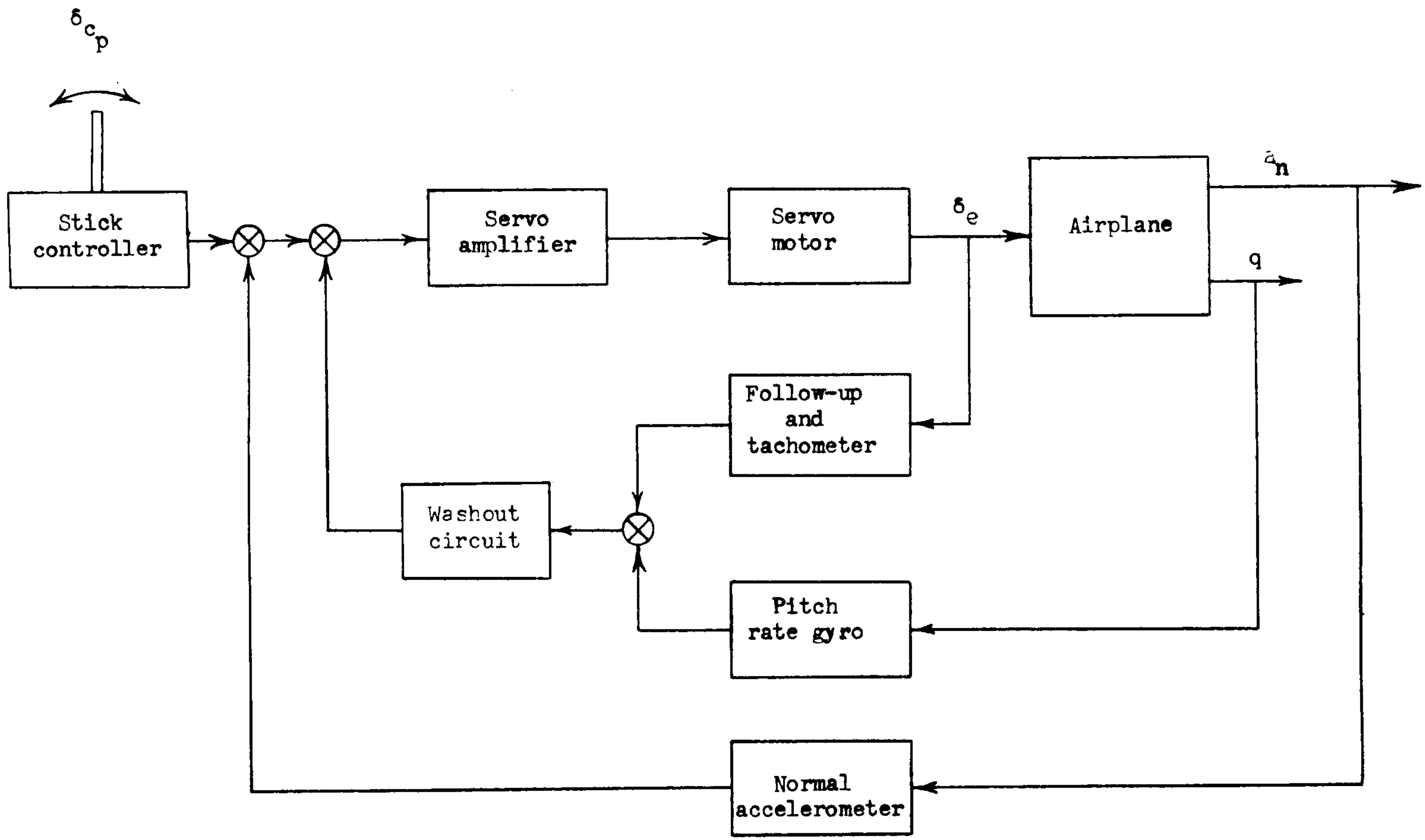
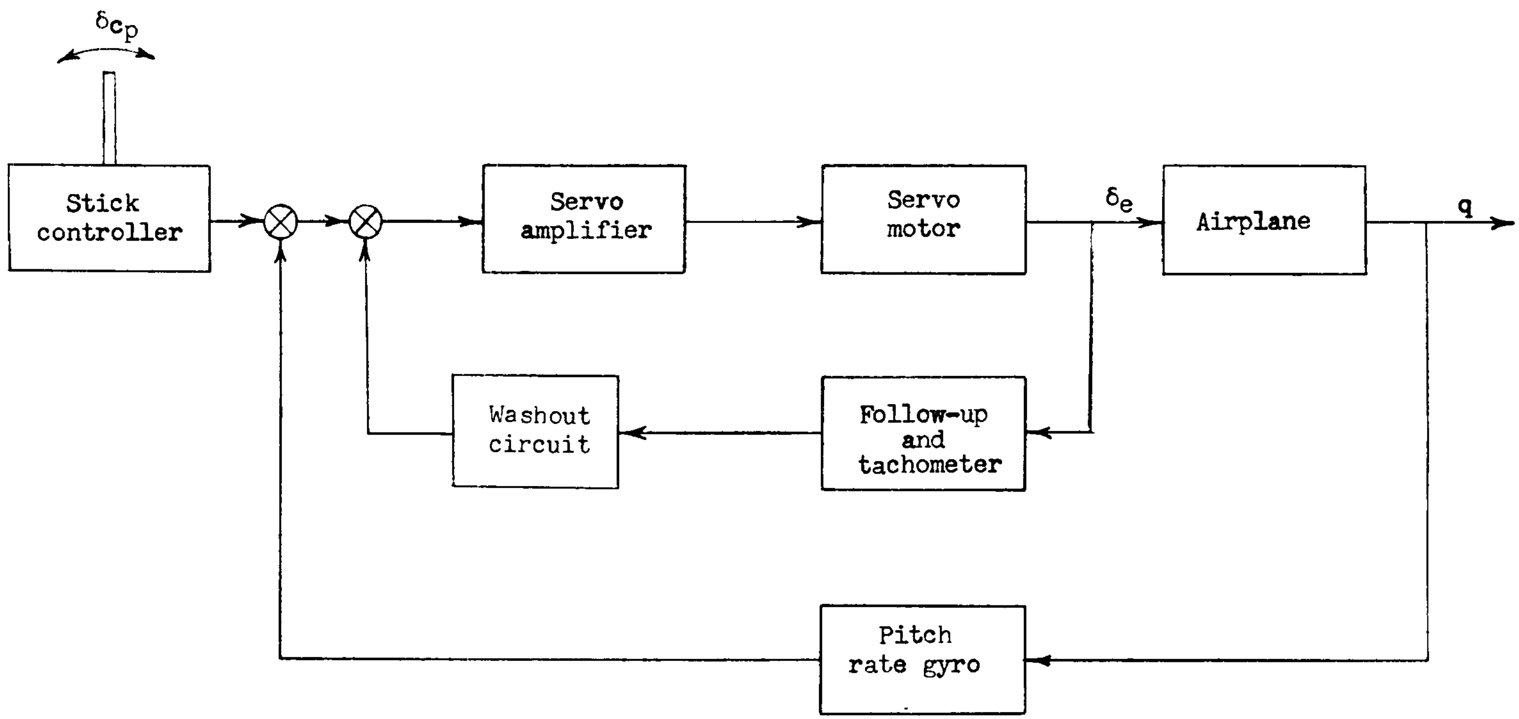


Figure 3.- Force-deflection characteristics of basic-airplane longitudinal control system as measured on the ground. The elevator system includes a spring tab, a bobweight, and a light down spring.



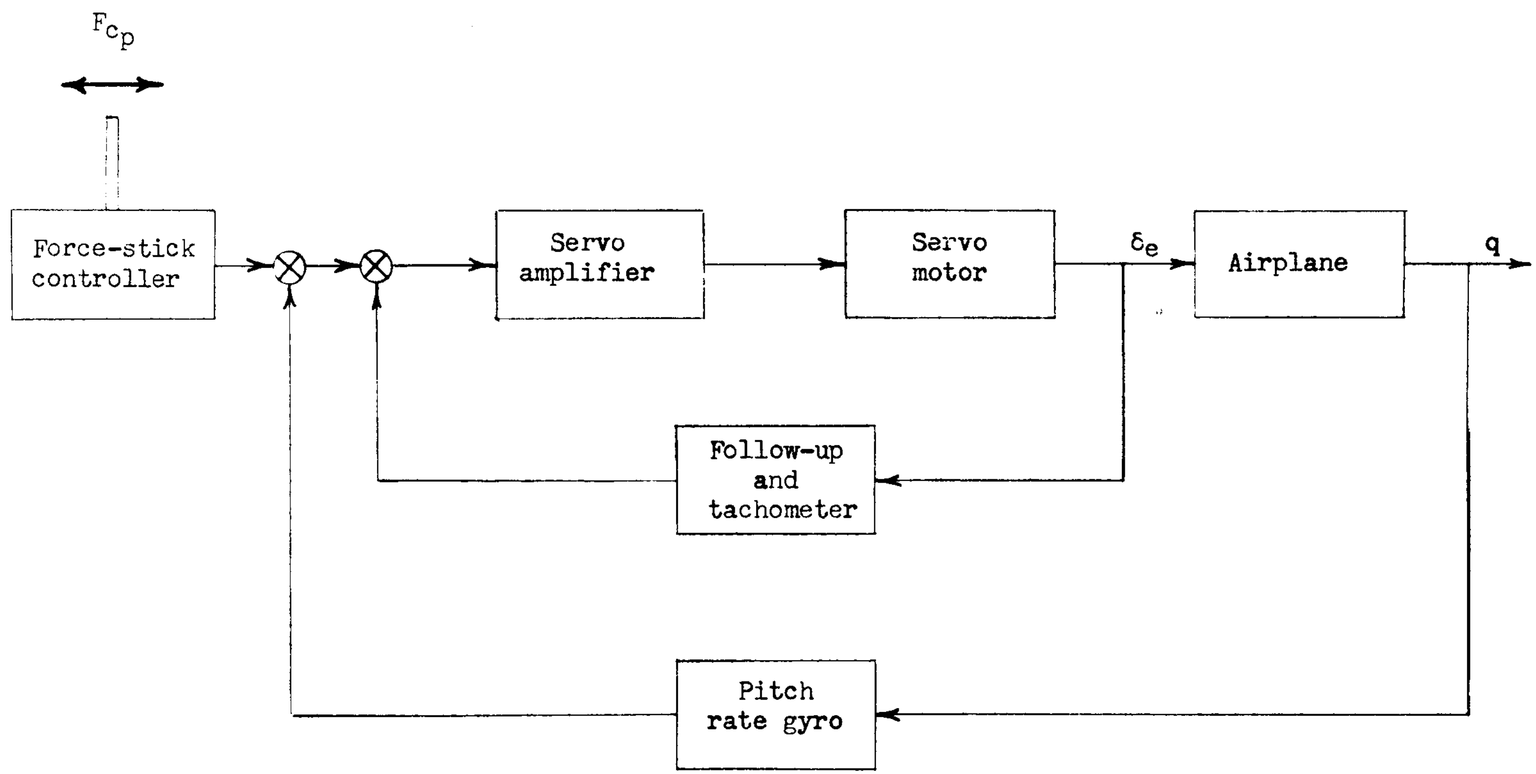
(a) Normal-acceleration-command control system.

Figure 4.- Block diagrams of the longitudinal stabilization and control systems.



(b) Pitch-rate-command control system.

Figure 4.- Continued.



(c) Pitch-damper system.

Figure 4.- Concluded.

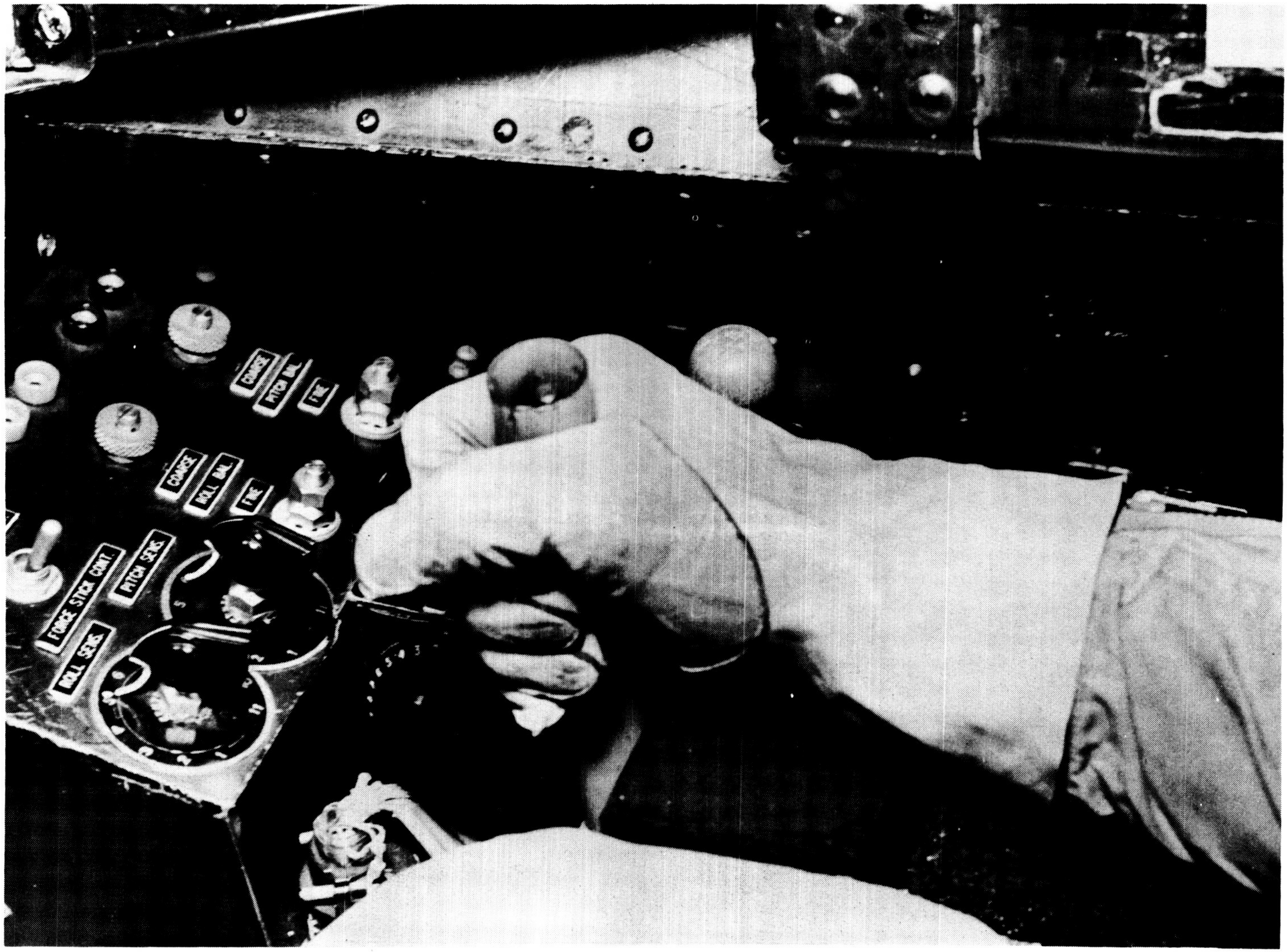


Figure 5.- Photograph of side-located force stick. L-59-6030

Figure 6.- Photograph of side-located control stick. L-94832.2

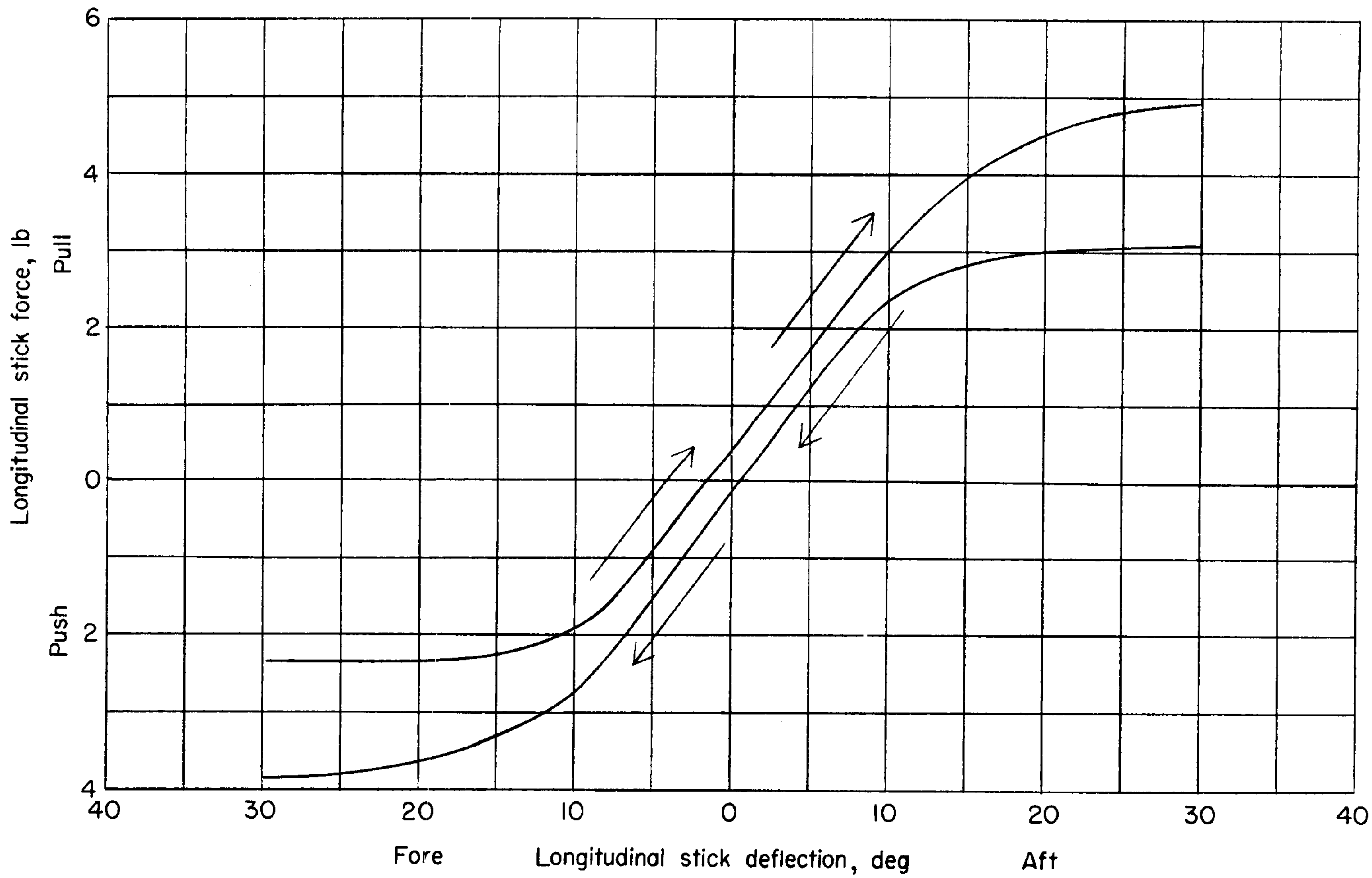


Figure 7.- Force-deflection characteristics of side-located control stick. Force is based on a 2.75-inch moment arm.

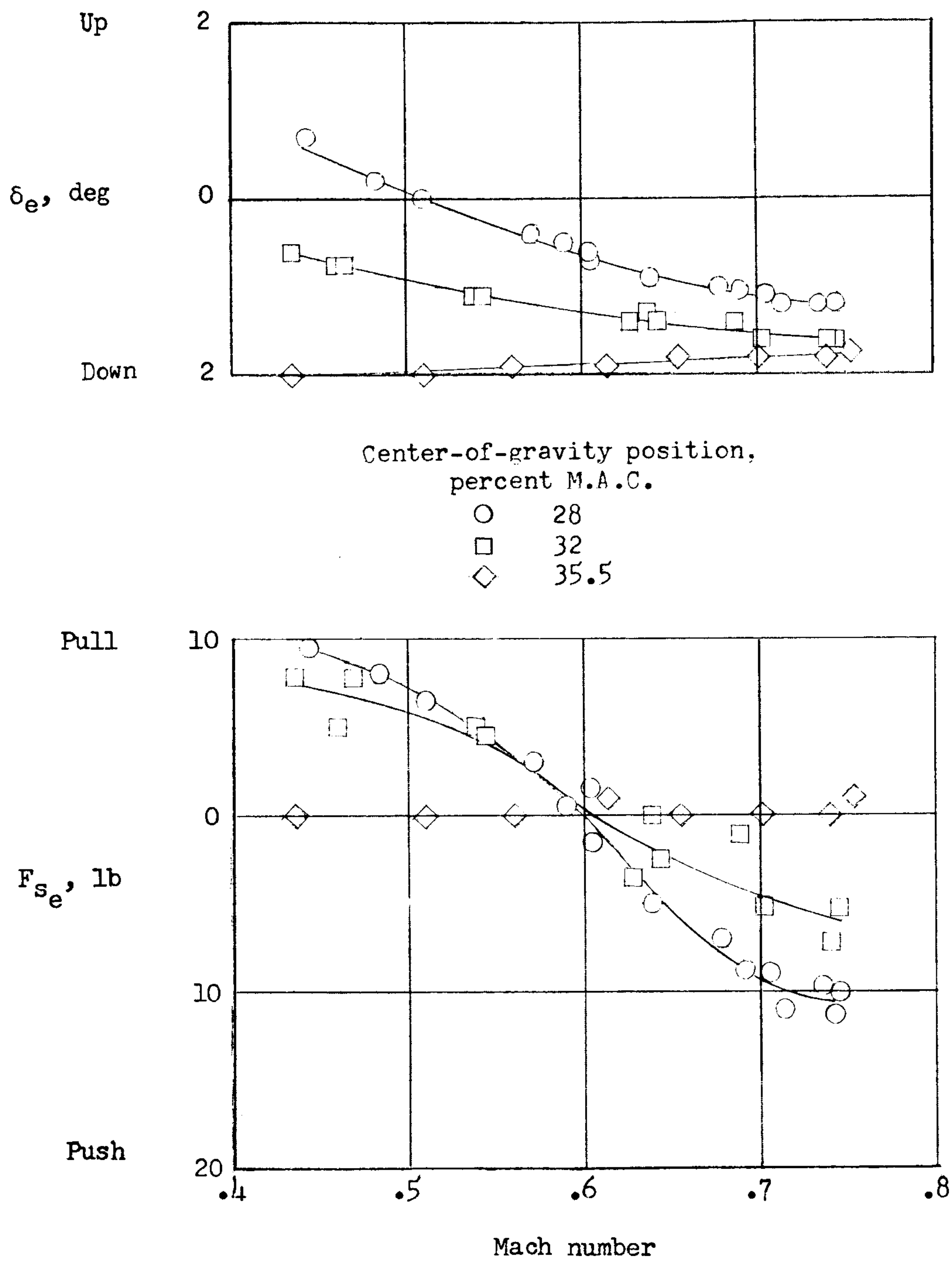


Figure 8.- Static longitudinal stability characteristics of the basic airplane in the clean condition at three center-of-gravity positions. h_p = 30,000 ft; power for level flight at M = 0.6.

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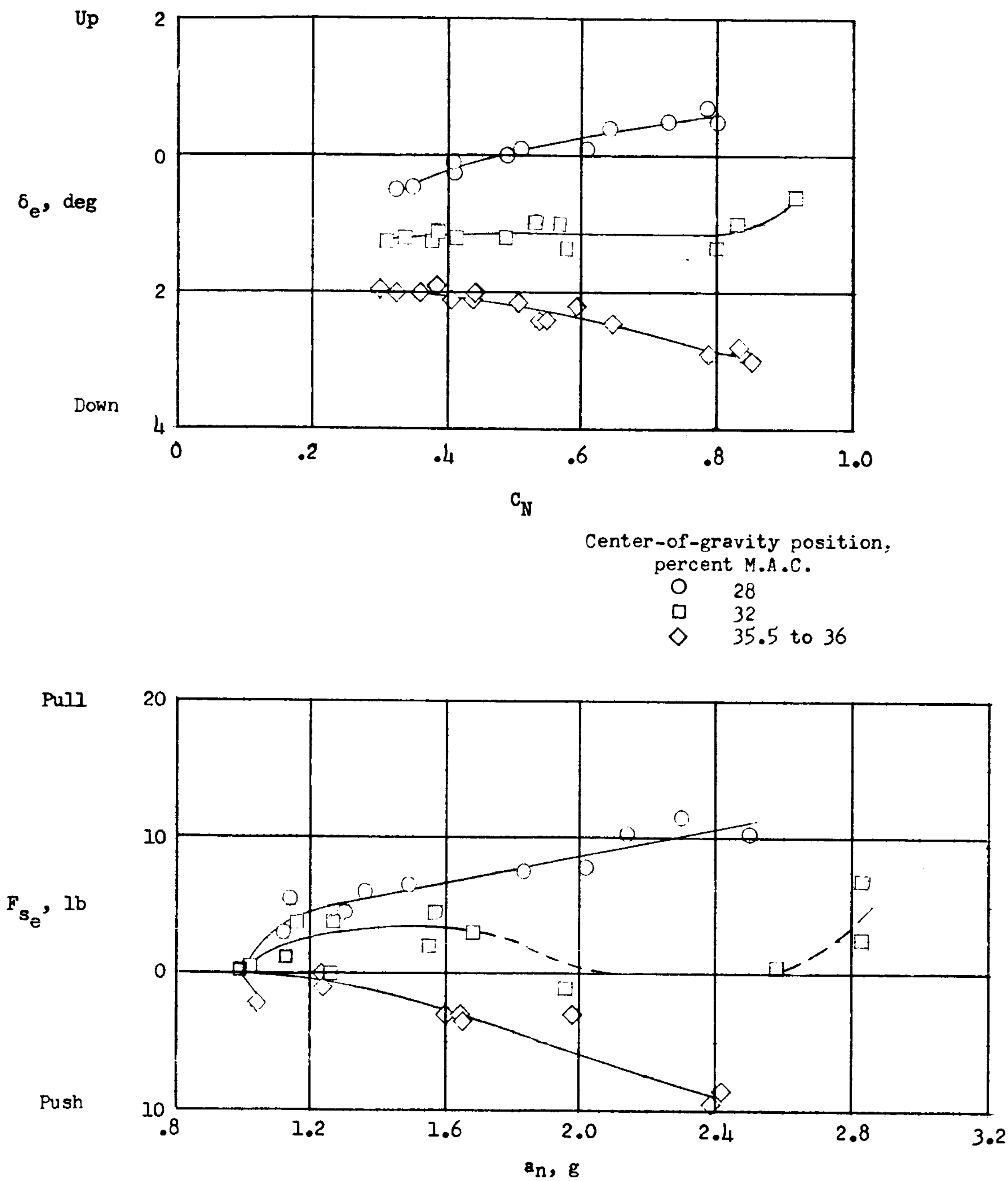

Figure 9.- Maneuvering longitudinal stability characteristics of the basic airplane in the clean condition at three center-of-gravity positions measured in steady turns. M = 0.6; h_p = 30,000 ft; power for level flight.

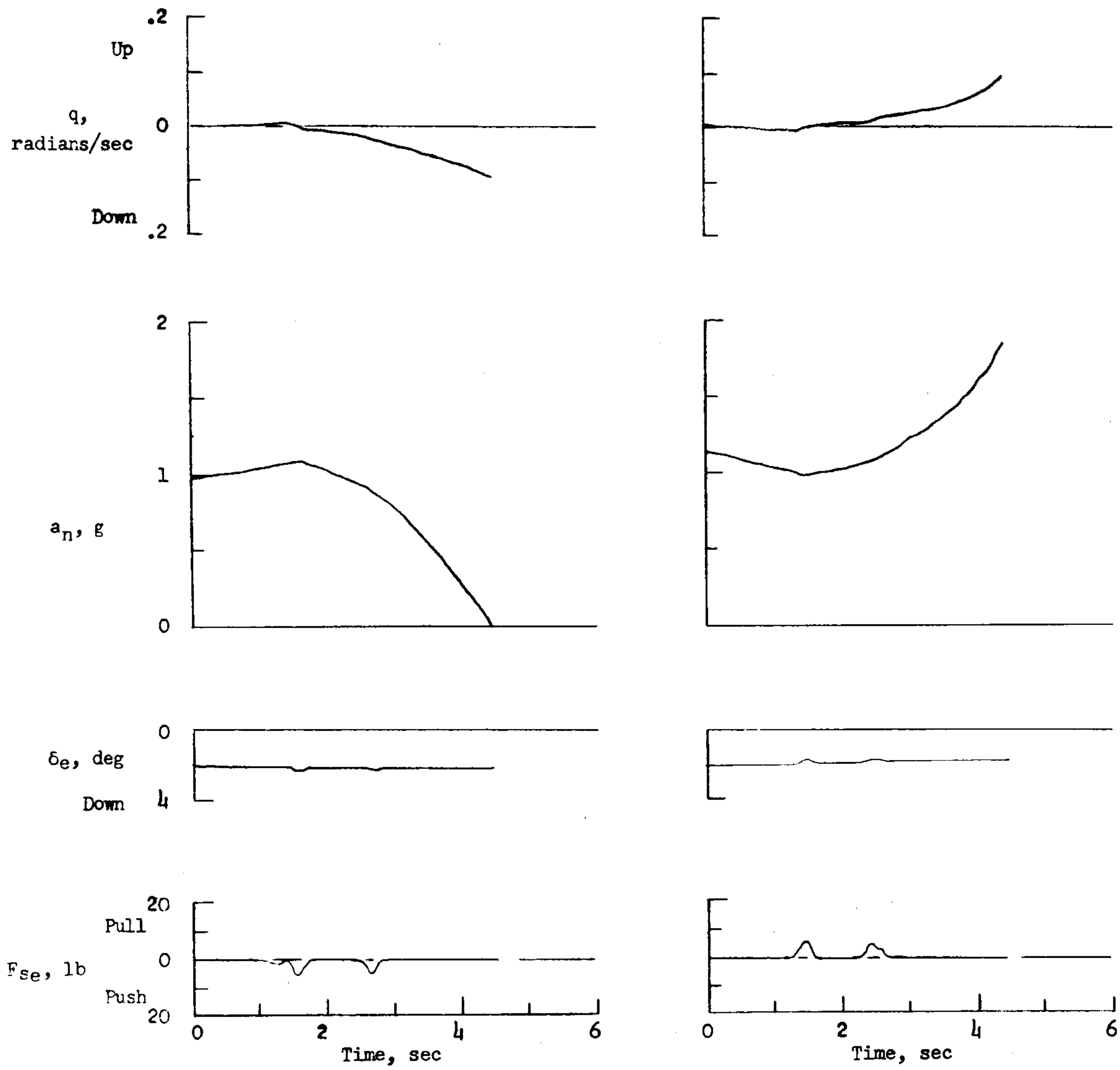

Figure 10.- Time histories of divergences for basic airplane following stick pulses. Center-of-gravity position at about 36 percent mean aerodynamic chord; M = 0.6; h_p = 30,000 ft.

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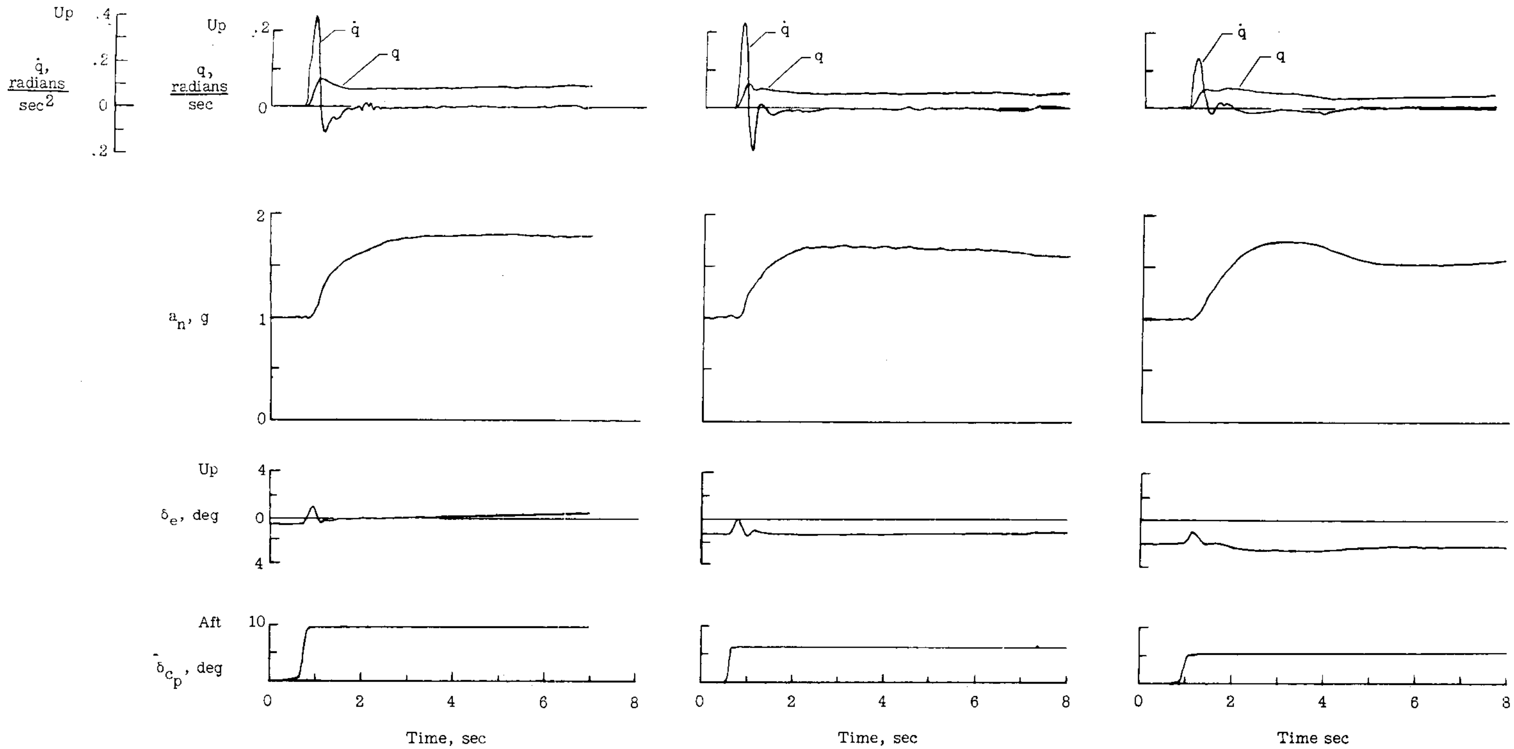


(a) Center of gravity at 28 percent mean aerodynamic chord.

(b) Center of gravity at 32 percent mean aerodynamic chord.

(c) Center of gravity at 36 percent mean aerodynamic chord.

Figure 11.- Transient responses of the normal-acceleration-system—airplane combination at three center-of-gravity positions. $M = 0.6$; $h_p = 30,000$ ft; the side-located displacement stick was used for these runs; elevator position feedback gain, 0.93 volt/deg; pitch-rate gain, 23 volts/radian/sec; acceleration gain, 2.7 volts/g; canceler time approximately $1\frac{1}{4}$ seconds.

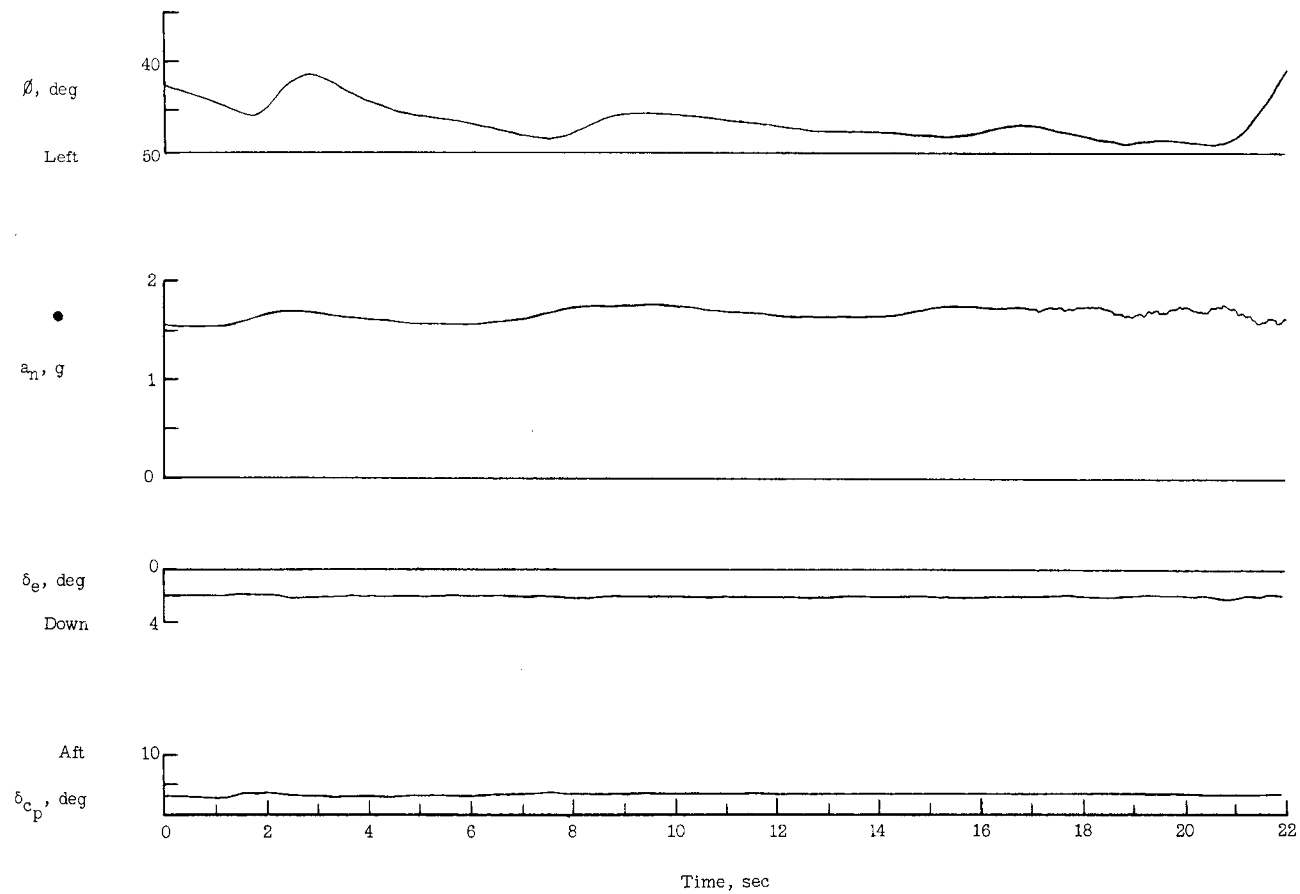


Figure 12.- Time history of portion of steady left turn. Normal-acceleration system with side-located displacement stick. $M = 0.6$; $h_p = 30{,}000$ ft; center of gravity at 36 percent mean aerodynamic chord; elevator position feedback gain, 0.93 volt/deg; pitch-rate gain, 23 volts/radian/sec; acceleration gain, 2.7 volts/g; canceler time constant approximately $1\frac{1}{4}$ seconds.

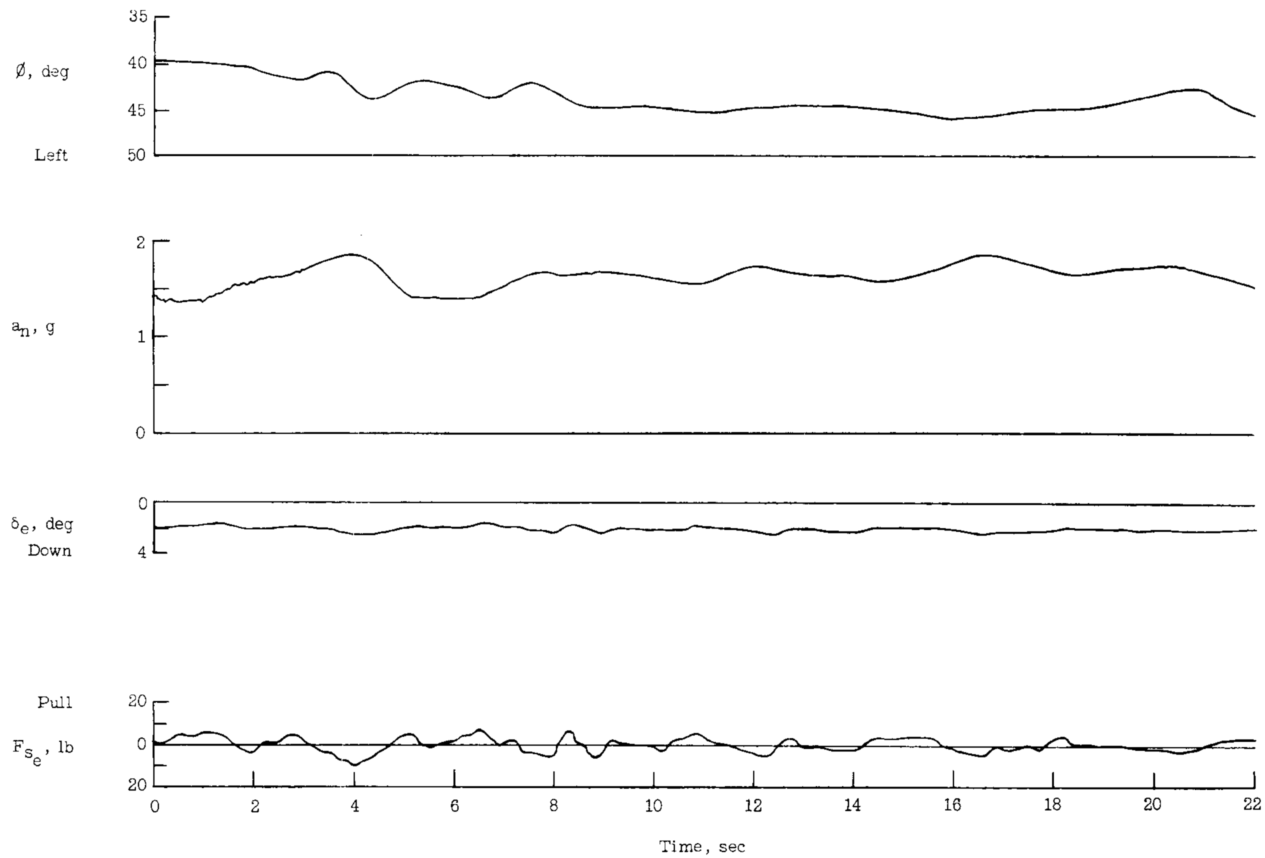
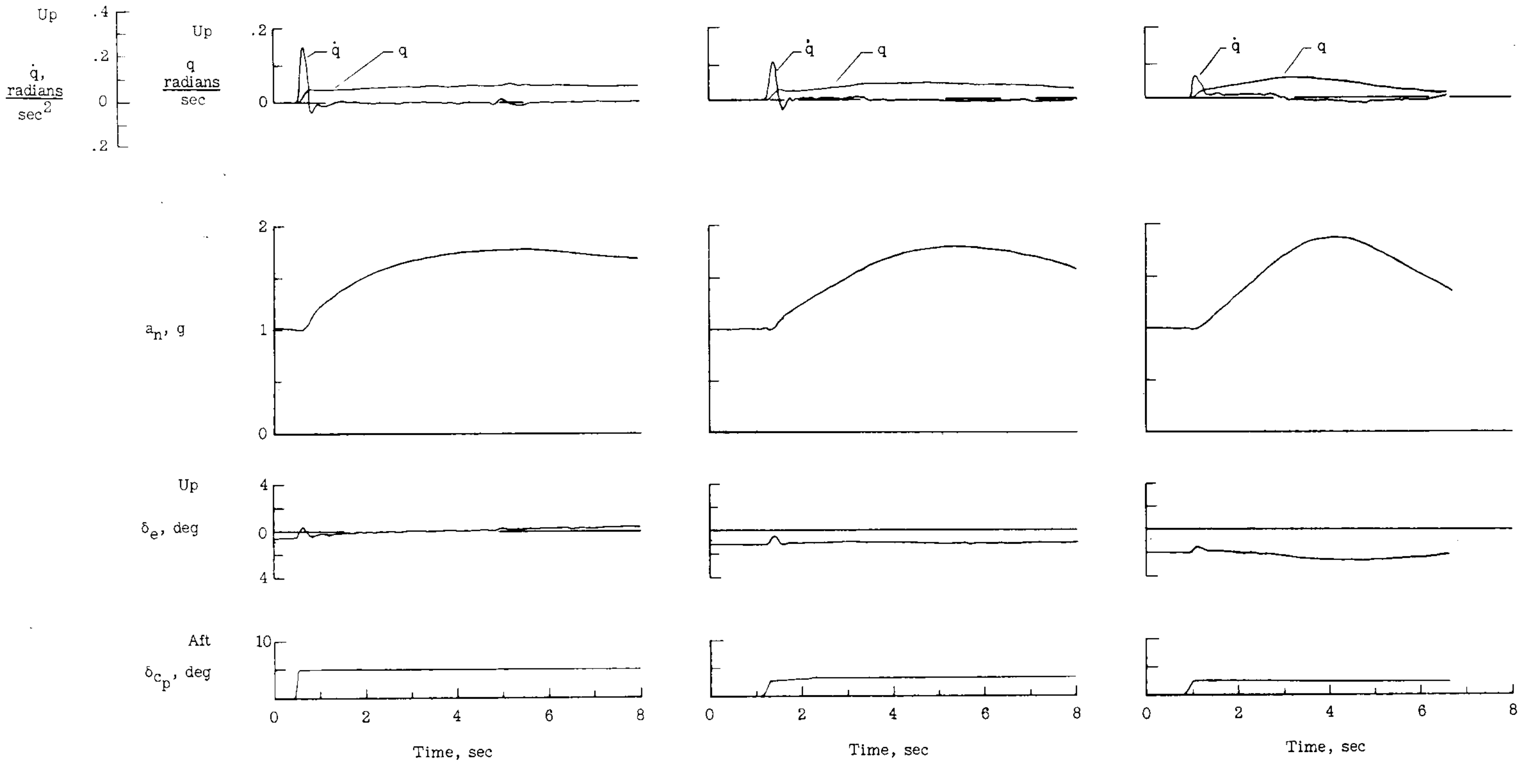


Figure 13.- Time history of a portion of a left turn. Basic-airplane control system; M = 0.6; h_p = 30,000 ft; center of gravity at 36 percent mean aerodynamic chord.



(a) Center of gravity at 28 percent mean aerodynamic chord.

(b) Center of gravity at 32 percent mean aerodynamic chord.

(c) Center of gravity at 36 percent mean aerodynamic chord.

Figure 14.- Transient responses of the pitch-rate-control-system—airplane combination at three center-of-gravity positions. $M = 0.6$; $h_p = 30{,}000$ ft; the side-located displacement stick was used for these runs; pitch-rate gain, 23 volts/radian/sec; elevator position feedback gain, 0.93 volt/deg; canceler time constant approximately $1\frac{1}{4}$ seconds.

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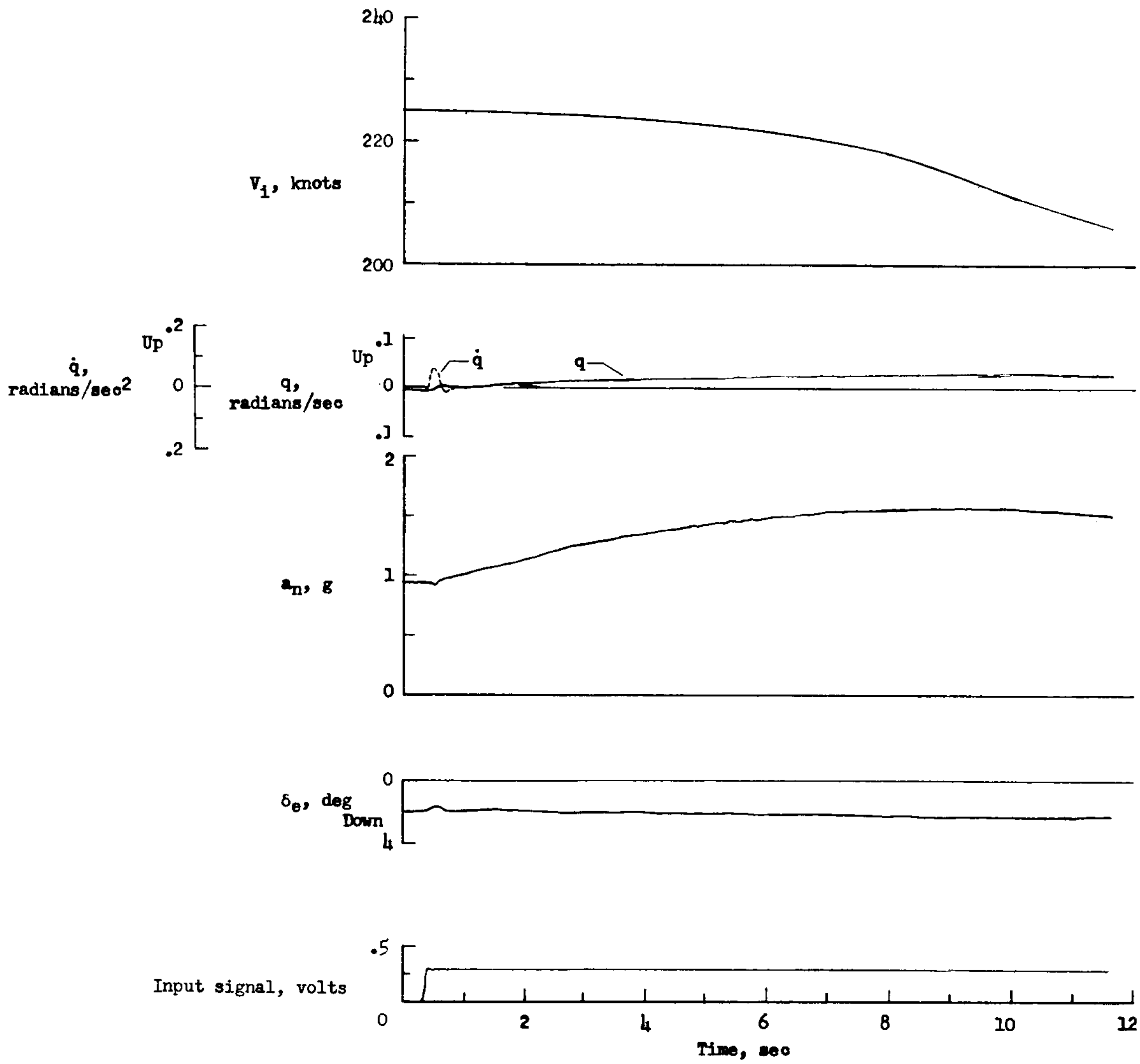
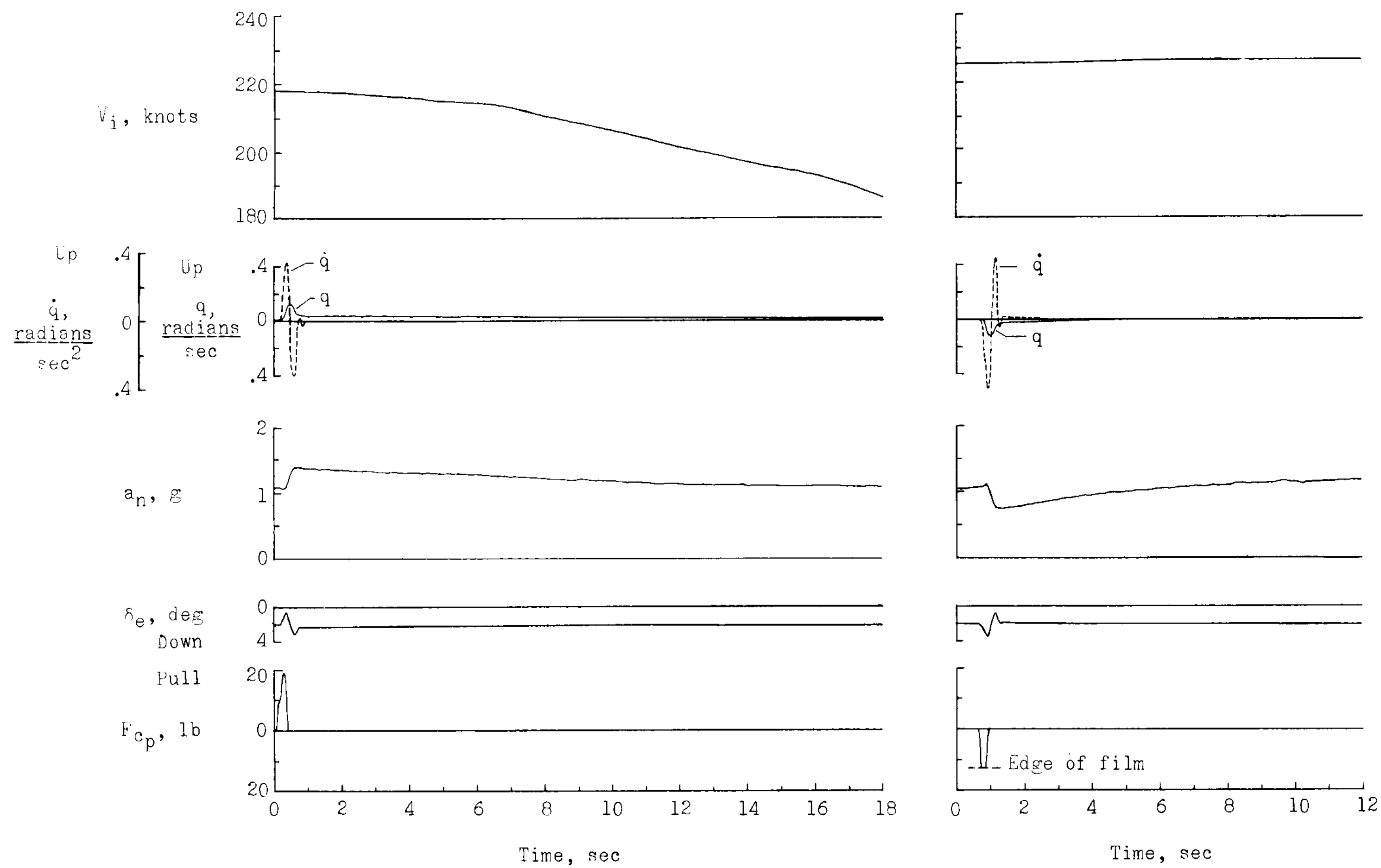


Figure 15.- Transient response characteristics with pitch-damper system. M = 0.6; h_p = 30,000 ft; center of gravity at 36 percent mean aerodynamic chord; pitch-rate feedback gain, 23 volts per radian/sec; elevator position feedback gain, 0.93 volt/deg.



(a) Noseup pulse.

(b) Nose-down pulse.

Figure 16.- Responses of the airplane—pitch-damper combination to pulse inputs. $M = 0.6$; $h_p = 30{,}000$ ft; center of gravity at 36 percent mean aerodynamic chord; pitch-rate feed-back gain, 23 volts/radian/sec.